MSG-EAR-00282
April 2, 2001

Thermal Stress Analysis of Numi Baffle – II

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Introduction

The previous finite element analysis of the aluminum baffle assumed that the baffle would see a maximum of five beam pulses, centered at approximately 1 cm from the baffle axis. No heat transfer was assumed at the boundary; i.e., the model was adiabatic.

Three objections were raised to this characterization. First, the number of beam pulses was deemed too small, and in fact, it was argued that the baffle must survive for an indefinite length of time in the beam. Second, the centering of the beam at 1 cm radius (inner radius is 0.5 cm, so impingement occurred at 5mm beyond the inner radius of the collimator) was thought to be non-conservative from the standpoint of creating a "worst case" for analysis. And third, 6061-T6 data indicate that, at high temperatures, the yield stress will drop substantially below the 35 ksi room-temperature value assumed in the first analysis.

The adiabatic assumption is unsuitable for a steady-state analysis. Therefore, for this work it is assumed that the outside surface of the baffle was maintained at 25 C. Given the baffle length (117 cm) and outer radius (15 cm), and the total steady state heat load of 116 kW, the required heat transfer from the surface is 10.5 W/cm^2.

Summary

The analysis shows that the maximum baffle temperature will level off at approximately 320 C after one hundred pulses. This temperature is beyond the upper limit of 204 C permitted by the ASME Code for 6061-T6

Large plastic deformations occur, and "shakedown" to purely elastic action is likely to take at least 100 pulses. This number is approximate, given that the properties of the aluminum at 300 C are not well-represented.

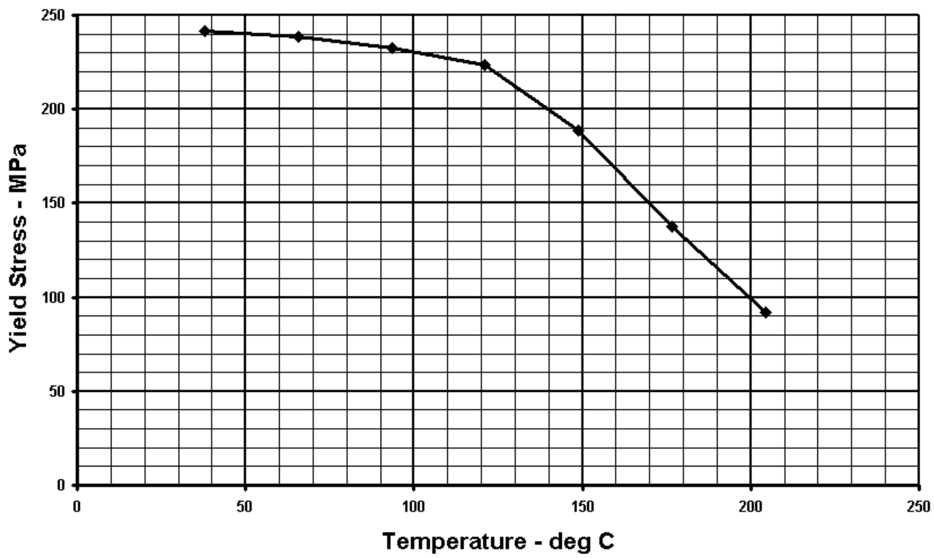
Dynamic stresses do not appear to present any difficulties.

In view of the high temperature, and the uncertainty of the material properties, the actual plastic deformation and thermal ratcheting behavior cannot be assumed to be represented by this analysis. Therefore, it is recommended that an all-aluminum baffle be abandoned in favor of a design which can be analyzed with more confidence.

Yield Stress of 6061-T6

The ASME Boiler and Pressure Vessel Code gives the minimum specified yield stress for 6061-T6 for temperatures of from 0 – 200 C. These are plotted in Fig. 1.
The figure shows a severe reduction in yield stress beginning at about 120 C. At 200 C

Fig. 1. Yield Stress of 6061-T6 as Function of Temperature (from ASME Code - II-D)



the yield stress has fallen to less that 40% of its room temperature value.

The ASME Code does not permit the use of 6061-T6 above a temperature of 400 F (204 C)

Thermal Analyses

The finite element model of Fig. 2 was used to determine the maximum temperature of the baffle under steady-state beam bombardment. It is a half-model consisting of approximately 120k elements and nodes. Elements were 8-node bricks.

The first step was to determine the difference in maximum temperature between the case where the beam impinged at a distance of 5mm beyond the inner radius, and the case where the beam impinged at a distance of 2mm beyond the inner radius. The heat generation data were generated only for the 5mm case; no data specific to the 2mm case were available. Therefore, the 2mm case was approximated by simply generating the collimator 3mm higher in space, and using the same heat generation data as were used for the 5mm impingement, but applied to the moved elements.

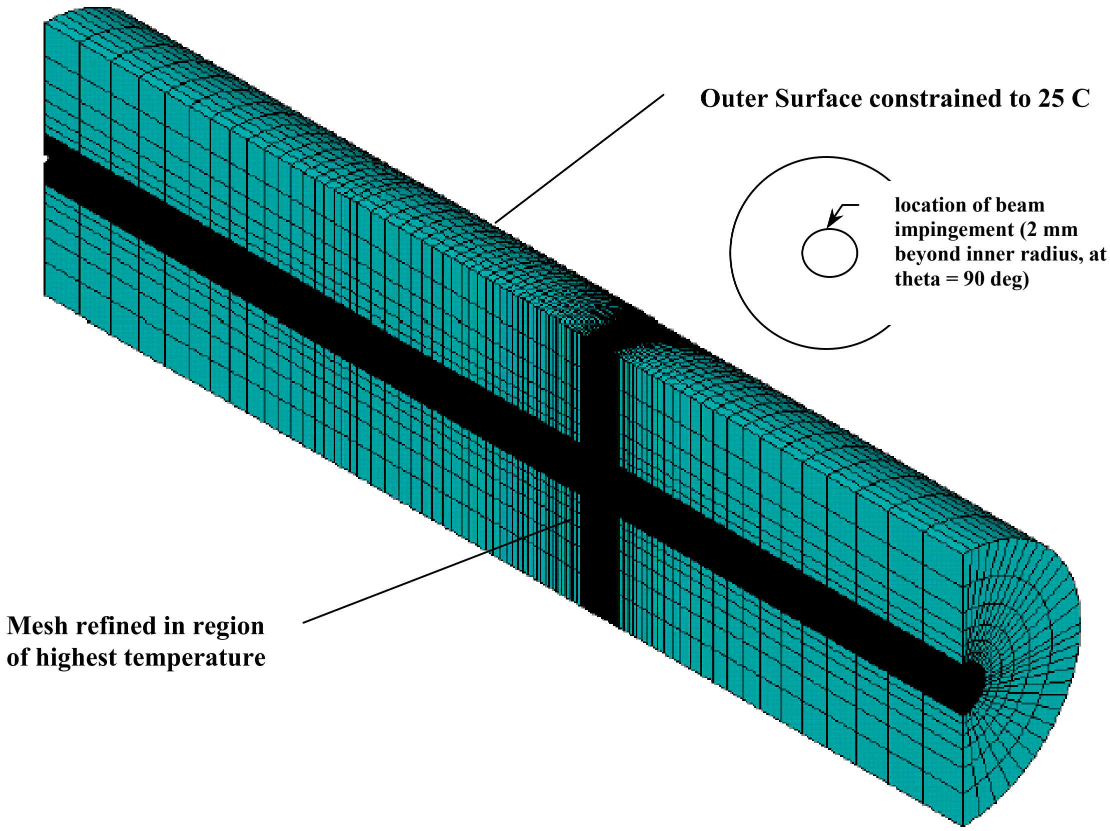


Figure 2. Finite Element Thermal Model

Fig. 3 shows that the 2mm impingement produces slightly higher maximum temperatures, and slightly lower minimum temperatures. This is clarified in Fig. 4. The lower minimum temperature is due to the greater localized heating for the 2mm case, and the larger thermal gradients which produce greater heat transfer from the affected volume during the latent period between pulses. After ten cycles, the maximum and minimum temperature differences level off to approximately 8 C and -6 C, respectively.

Fig. 3. Baffle Temperature Rise for 2mm and 5mm Beam Impingements - 10 cycles

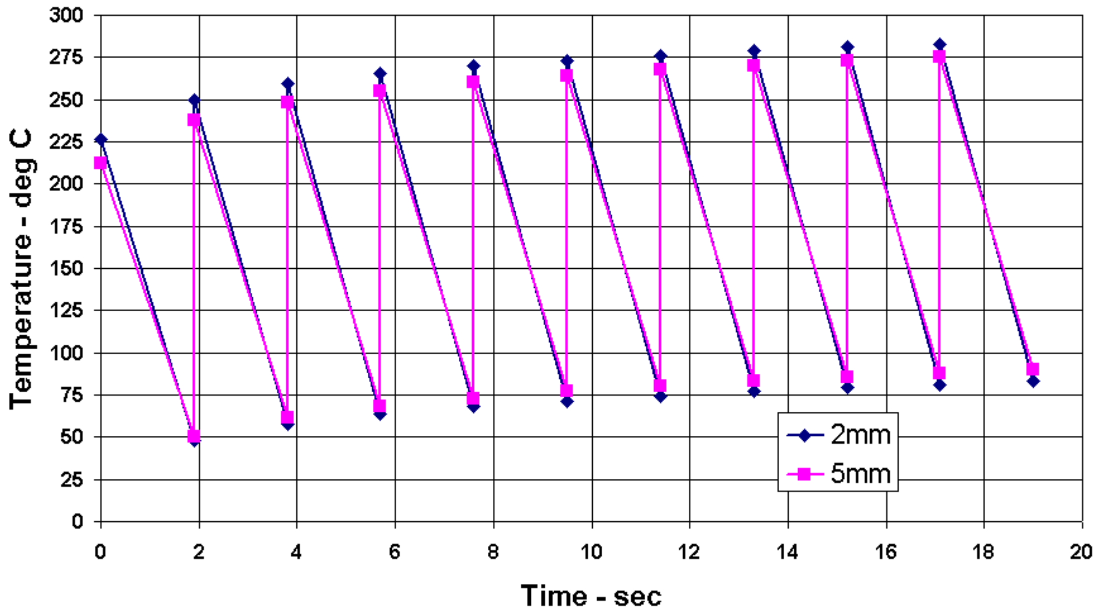
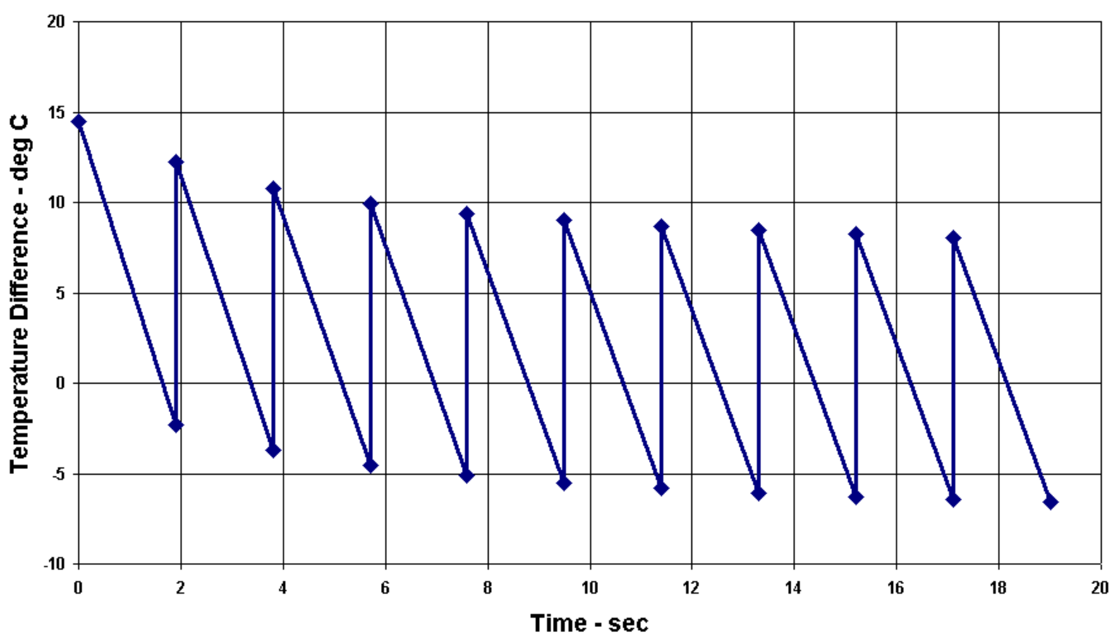


Fig. 4. Temperature Difference for 2mm and 5mm Impingements - 10 cycles



To determine the maximum temperature reached by the baffle in the steady-state condition, the FE model of Fig. 2 was run for 300 beam pulses at the 5mm impingement. The results are shown in Fig. 5. The maximum temperature of the baffle levels off to 315 degrees by the 250th cycle (500 seconds). From the previous results it can be inferred that the 2mm impingement would level off at approximately 323 degrees over the same length of time.

Fig. 5. Baffle Temperature Rise for 5mm Impingement - 300 cycles

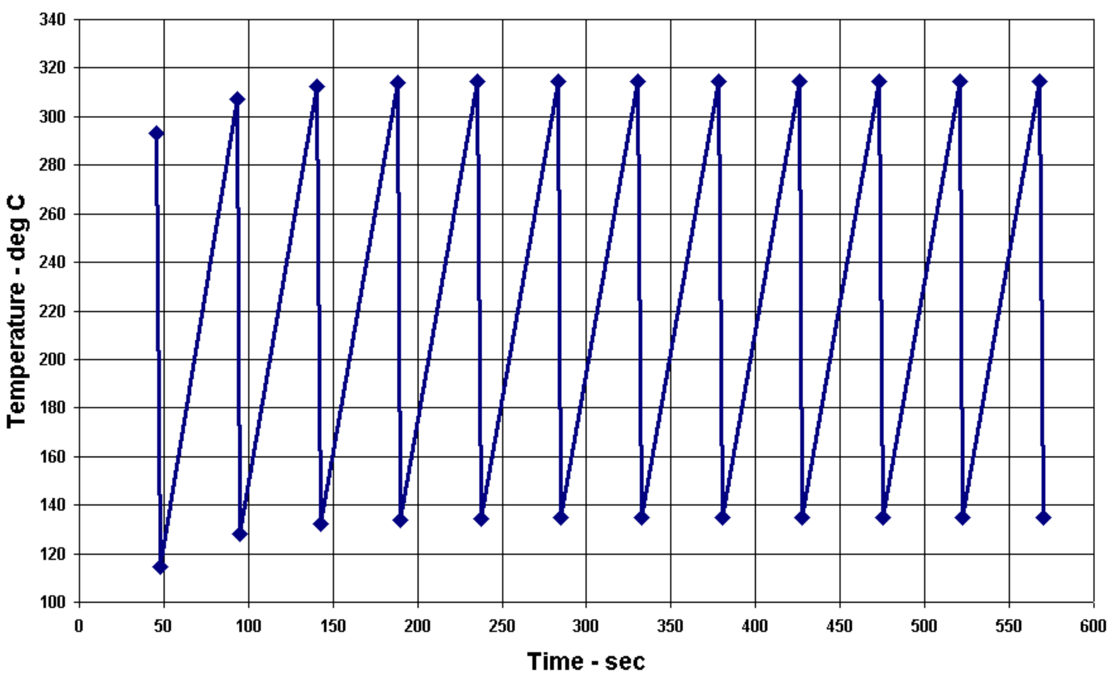
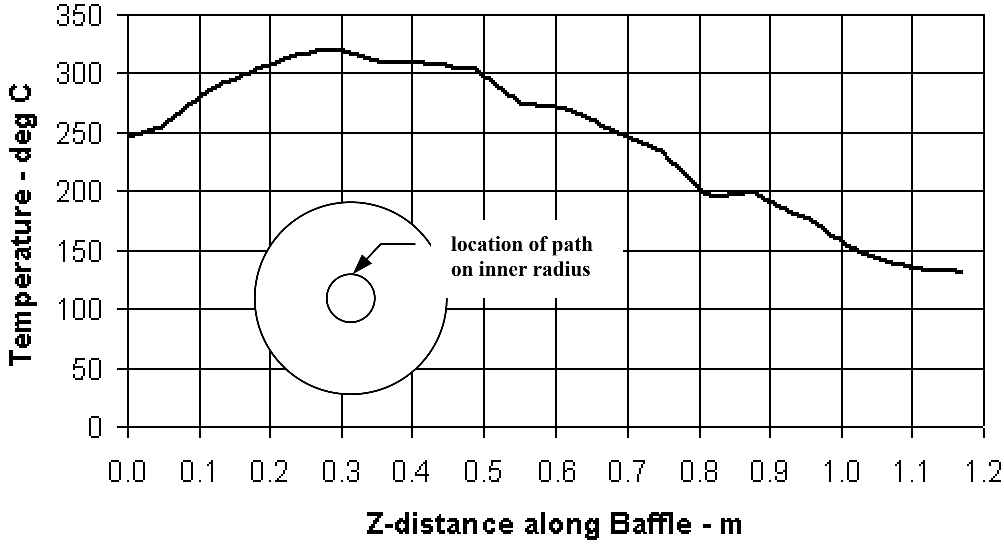


Figure 6 shows the temperature profile along the inner radius of the baffle at 90 degrees, at the end of a pulse, in the steady-state condition (>500 seconds)

Figure 6. Temperature Profile along Inner Radius at end of Pulse - Steady State (initial T = 25 C)



Stress Analysis

Three approaches were taken in the stress analysis:

1. Plastic, small deformation, no inertia effects, steady state
2. Plastic, large deformation, no inertia effects, fifteen pulses
3. Elastic, small deformation, inertia effects, one pulse

The first approach considers the nonlinear stress-strain characteristics of the baffle, but does not consider any physical lengthening or shortening that might result from that plasticity. It also does not include any effects related to the generation and propagation of stress waves (dynamic stresses)

The second approach considers nonlinear stress-strain, but allows the build-up of physical dimension during the analysis, and thus takes into consideration thermal ratcheting. It does not consider dynamic stresses. The fifteen pulses are based on the maximum, steady state temperature profile.

The third approach looks at the elastic stress wave in the baffle, but does not include either non-linear stress-strain, or large deformation effects.

Plastic, small deformation, no inertia effects, steady state

The structural finite element model for plasticity used a bilinear kinematic material assumption, based on the yield stress curve of Fig. 1. This method assumes that post-yield behavior is linear, but at a much reduced stiffness. For this analysis, the post-yield stiffness (tangent modulus) was chosen to be 10% of the room-temperature yield.

The curves used in this analysis are shown in Fig. 7.

Figure 7. Bi-linear Stress-Strain Curves used for Plasticity Analyses

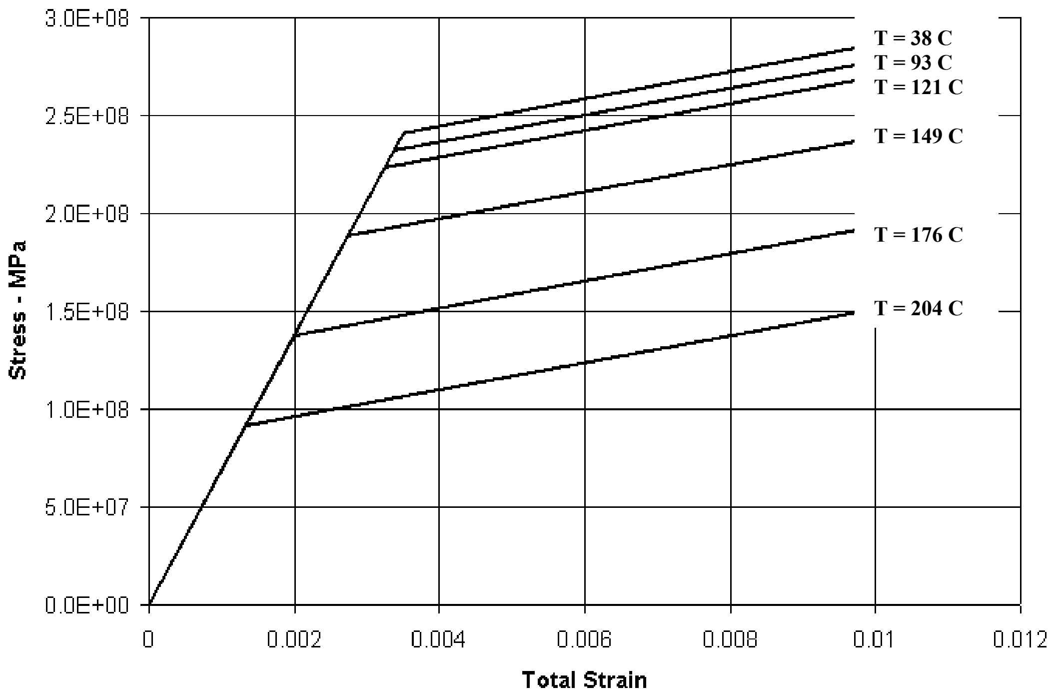
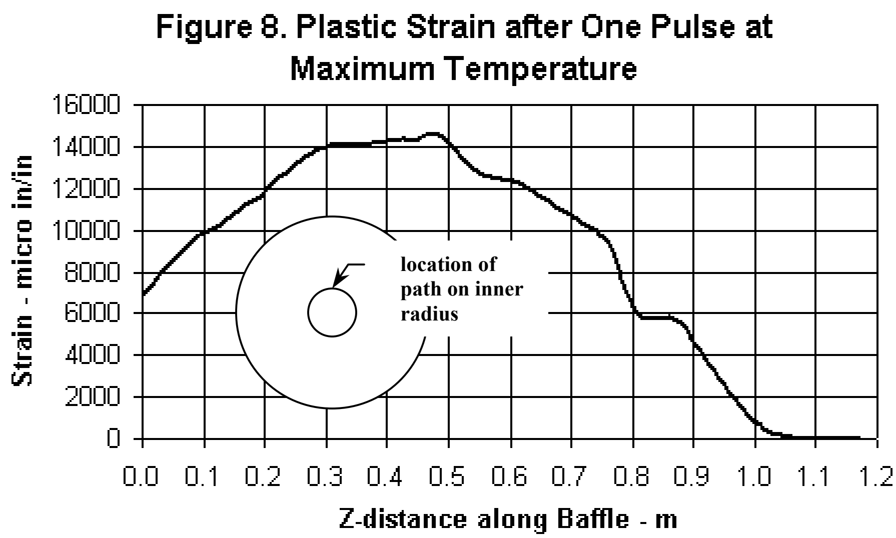


Fig. 8 shows the plastic component of strain along the inner radius of the baffle at 90 degrees, at the end of one pulse at the steady-state maximum temperature. The location of the maximum plastic strains correspond to the locations of maximum temperatures shown in Fig. 6. Plasticity occurs over a 1 meter length of the inner radius of the baffle. The approximate volume of yielded material is 10 cubic centimeters.

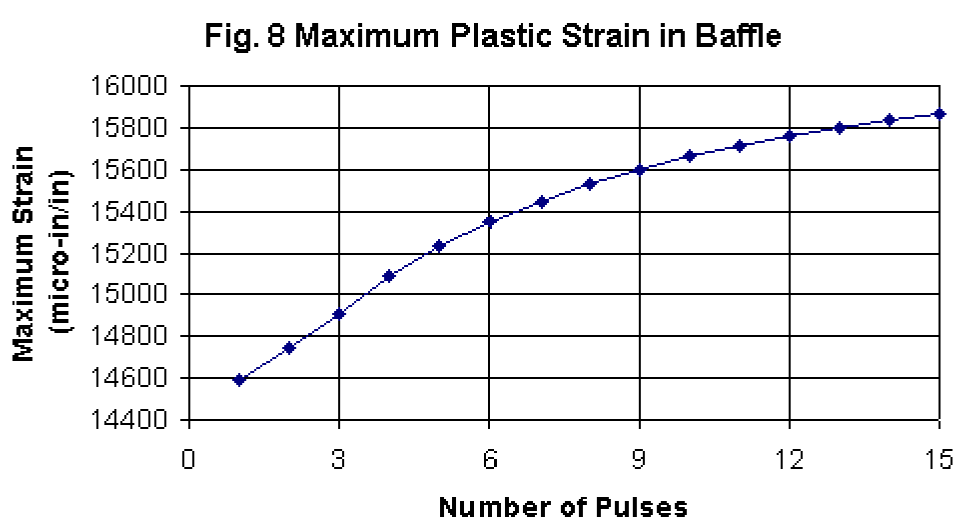


Plastic, large deformation, no inertia effects, fifteen pulses

The large temperature gradients, combined with the cyclic loading and reduced yield strength of 6061-T6 at high temperatures, produce plasticity in the baffle. This plasticity causes the physical dimensions to change, and will induce thermal ratcheting. This is a phenomena caused by progressive plastic distortions, i.e., the plastic elongations produced by one thermal cycle are added to the initial length that will distort under the next cycle, producing additional plastic strain, possibly to the point of deforming the baffle beyond the point of usefulness.

To estimate this behavior, the finite element model of Fig. 2 was subjected to fifteen pulses at the maximum temperature. The program was adjusted to account for both plasticity and the increase in dimension of the baffle as it deformed.

The maximum plastic strains for each cycle are shown in Fig. 8

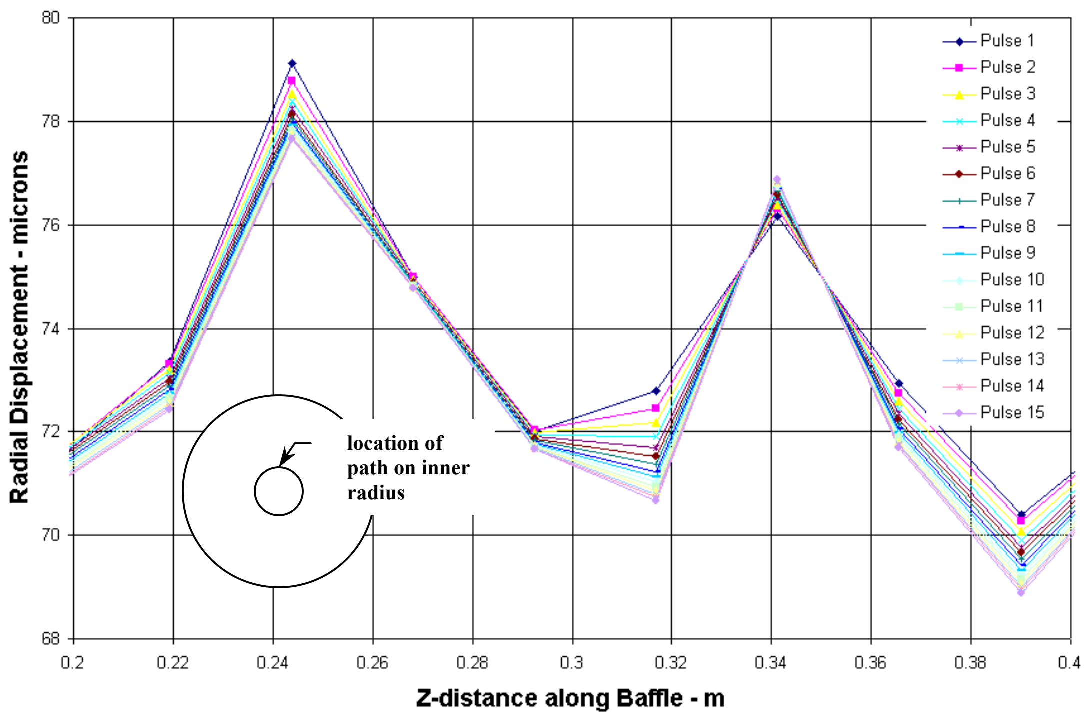


The figure shows progressive thermal distortions, which appear to be leveling off (a process known as "shakedown") at less than 100 pulses.

The effect of this ratcheting on actual radial displacements is shown in Fig. 9. The most heavily plastic region (from 0.2 < Z < 0.4 m) is shown, with displacements plotted for each of fifteen pulses. The material at Z = 0.32m is particularly highly strained, though all of the points in this range show deformations that increase or decrease with successive pulses.

<u>Explanation of Trends</u>: Radial displacements in the heated region tend to be positive, i.e., outward. This is the simple result of thermal expansion. The tendency for some displacements to decrease is explained by the interaction with large compressive axial strains, which will produce radial strain due to the Poisson effect. This appears to be what is happening in the region shown in Fig. 9, where each successive pulse actually reduces the radial displacement over much of the range.

Figure. 9. Radial Displacements along Inner Radius - 15 pulses



Elastic, small deformation, inertia effects, one pulse

The speed of sound in aluminum is approximately 5000 M/sec. Given the dimensions of the baffle, any stress wave produced by the sudden imposition of a thermal gradient at the inner radius will not have reached the outer radius before the end of the pulse (10 microseconds.)

Modeling to accurately capture the stress wave in such a short time is demanding of both computer resources and time. An elastic model, using 20-node brick elements, and refined in the region of highest temperature, was used. The 10 microsecond interval was broken into 0.02 microsecond increments, during which time a stress wave will travel approximately 0.1 mm. The temperature load was ramped linearly from 25 C to its final distribution at 10 microseconds.

From the results, the maximum radial stress was found at Z = 0 m (upstream face); the maximum compressive axial stress was found at Z = 0.32 m. These stresses are shown in Figs. 10 and 11.

Figure 10. Radial Stress -- Inner Radius @ Theta = 90, Z = 0 m as Function of Time for One Pulse

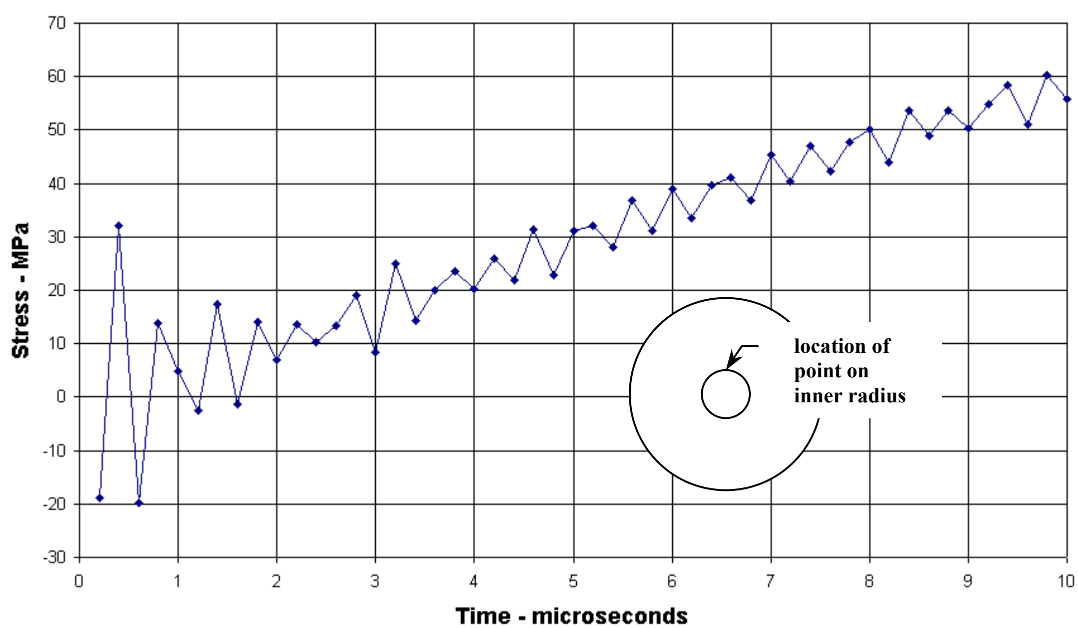
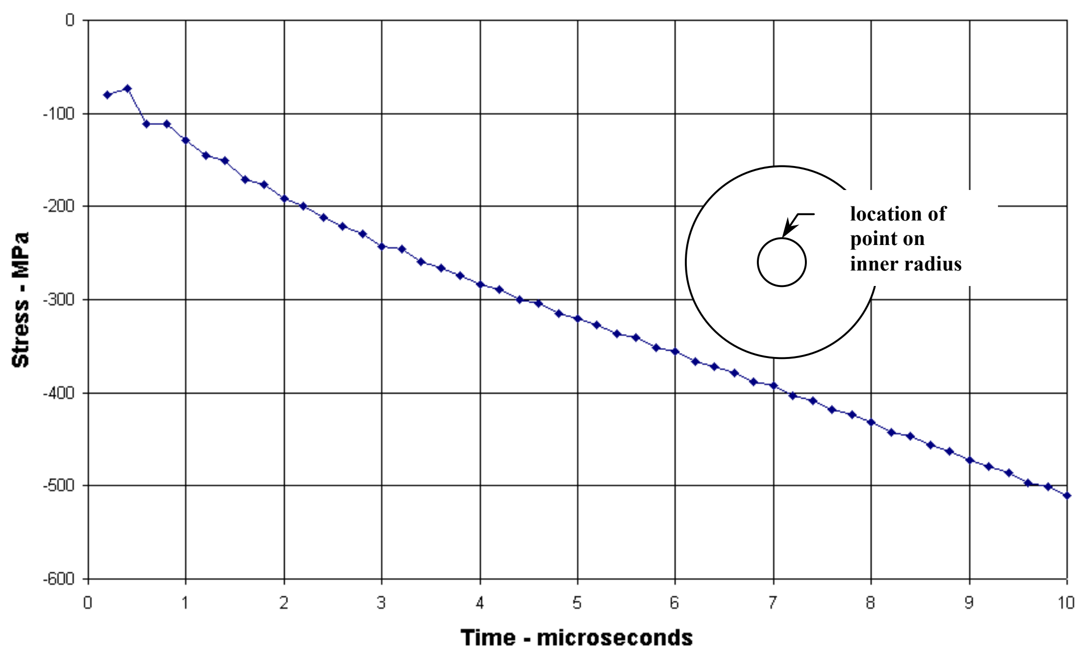


Figure 11. Axial Stress -- Inner Radius @ Theta = 90, Z = 0.32 m



From these results, it seems that a small disturbance occurs at t = 0.05 microseconds, after which both stresses follow a linear path to their final values at 10 microseconds. A separate run without dynamic effects confirms that the 10 microsecond final stresses are the same as those expected from the static analysis.

(It should be noted that the large compressive stresses are due to the elastic behavior of the material. The plastic analyses produces smaller stresses because yielding is considered.)

Conclusion

The aluminum baffle gets too hot to use; the material properties above 200 C are not known, and simple interpolation from the existing yield stress – temperature curves implies extremely low strength. The ASME Code does not permit this material to be used above 400 F (204 C). The properties used in this analysis are therefore inadequate to accurately predict plasticity, and even with these properties, serious thermal ratcheting considerations arise.

It is recommended that the aluminum baffle be abandoned, and a more robust design considered.